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Aerodynamic, stability and flying quality evaluation on a small blended wing-body aircraft with canard foreplanes

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Abstract

Blended wing-body (BWB) concept promises up to 30 percent increase in aerodynamic efficiency and reduction in fuel cost by having planform geometry optimized to increase lift and to reduce drag. Many claimed to have achieved the target of increasing lift-to-drag ratio better than current conventionally-configured airplanes either large airliners or small unmanned airplane. However, achieving good balance of aerodynamic efficiency, stability and flying quality is harder then one might expect. Over years of studying small BWB aircrafts in Universiti Teknologi MARA (UiTM), it is found that unconventional behaviour of aerodynamic characteristics leads to limitations to BWB aircraft's flight envelope. In this paper, a short overview of aerodynamic, stability and flying quality of UiTM's BWB aircraft design is highlighted. Lessons learned from its unsusual lift-angle of attack curves, stability reversals, the effect of canard to flight stability and poor longitudinal flying quality (short-period mode and phugoid mode) are discussed. A classical control solution to improve it flying quality has been proposed and simulated and the result shows that both short-period and phugoid modes are able to achieve damping ratios within 0.6 to 0.8 exceeding minimum Level 1 damping ratios of 0.35 and 0.04 respectively. Design flaws of this aircraft and recommendations to be implemented on the next evolution of aircraft design conclude this paper.

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Keywords: Blended Wing-Body; Unmanned Aerial Vehicle; Flight Dynamics; Aerodynamics

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1. Introduction

The challenge of improving flight performance, particularly range and endurance, had been undertaken since the early years of aviation. Flying wing is one of the solutions, introduced in Germany as a concept for long-range bombers [1], its use is limited to short years within the United States Air Force (USAF) in a form of B-49 [2]. Problems related to flight dynamics and control hampered the flying wing to serve in long years unlike its B-52 counterpart until advancement of digital fly-by-wire electronic control allowed the flying wing to be revived again in a form of B-2 stealth bomber [3]. It was also the time, in the late 1980s, when Blended Wing-Body (BWB) concept was introduced – a hybrid of flying wing and conventional tubular fuselage-wing-tail configuration [4].

Nomenclature

OFE	Operational Flight Envelope
P	Phugoid mode
SP	Short-period mode
c	Mean chord
C_D	Drag coefficient
C_L	Lift coefficient
C_M	Pitch moment coefficient
K_n	static margin, $K_n = h - h_n$
h	1. Centre of gravity location with respect to datum 2. altitude in feet
h_n	neutral point location with respect to datum
l_c	pitch moment arm for canard foreplane
η_c	canard incidence angle w.r.t. body x-axis
ω	Natural frequency
ζ	Damping ratio

The BWB concept promises up to 30% fuel consumption reduction by improving lift-to-drag ratio. It was found that the current airliners' conventional planform configuration had reach their limit of efficiency. Proposing flying wing airliners limits the passenger and cargo capacity thus a form of hybrid of the two different planform shape might be the answer. By carefully 'blending' the wing and body, removing tail and shaping the body like airfoil sections, one could reduce the wetted-surface area thus reducing skin friction drag, eliminate interference drag and increase lift [4]. This resulted in high lift-to-drag ratio, around 25 for some studies, compared with 18 for conventional configuration airliners while still carrying the same amount of passenger and payload [5, 6, 7, 8]. However, while BWB might poses the efficiency of a flying wing, it also inherit the latter's problems. Due to lack (or none) of horizontal tail and its relatively high pitch moment from its large lifting body, the BWB have serious problems with its longitudinal static stability and flying qualities [9, 10, 11]. Electronic controllers with advanced algorithm may provide stability augmentation but it may be forced to work all the time creating all sort of dynamically changing trim drag that reduces its aerodynamic efficiency (lift-to-drag ratio) [12].

BWB research team in Universiti Teknologi MARA was formed in 2005 with the first design, Baseline-I (HANTU), freezed and tested in wind tunnel within a year. The Baseline-I is a mere replica of Liebeck's planform with inspiration from the B-2 bomber albeit with intended use as a small two to four-metre span unmanned aircraft. It has the body span of 35 percent with body thickness-to-chord length ratio varies from 12 to 22 percent [13]. The study was extended to computational simulations to understand it aerodynamic behavior [14], implications to flight performance and flight stability and the effect of centre elevator to effectiveness of trim flight [15]. The second design took lessons learned from Baseline-I and used Inverse-Twist Method to design its planform and airfoil incidence [16]. The Baseline-II, introduced in 2009, had its body span reduced to just 19 percent, maximum body thickness reduced to 15 percent, larger wing area with high-wing location for lateral stability and smoother planform shape [17]. Canard foreplanes of various sizes were incorporated to reduce its nose-down stability and improve its agility [18].

This paper evaluates aerodynamics, stability and longitudinal flying quality of Baseline-II BWB. The governing standard for flying quality is based on MIL-F-8785C [20]. There are three issues related to this aircraft. They are;

- Aerodynamics - Each BWB design is unique and aerodynamic behaviour may also be unique. Many studies have investigated BWB aircraft dynamics and stability characteristics at high subsonic cruising speed (Mach 0.8 and above). Baseline-II BWB flies much slower (Mach 0.1) making its stability characteristic more vulnerable to aerodynamic parameters such as airspeed and altitude.
- Stability - Canard may destabilize an aircraft by shifting neutral point forward.
- Flying qualities - This aircraft must satisfy minimum requirement for Level 1 flying quality according to MIL-F-8785C. Small BWB may have similar aerodynamics to the larger BWB but the effect of velocity and altitude to flight dynamics is unknown.

In evaluating Baseline-II BWB behaviour, main questions to be answered are whether or not it adheres to static stability requirements and does so efficiently with small reduction in its maximum lift-to-drag ratio. Baseline-II E-2 BWB aircraft must also satisfy Level 1 flying qualities for both phugoid and short-period modes. If Baseline-II E-2 BWB aircraft need a stability augmentation system to improve its flying qualities what kind of control law shall be applied to the system for this aircraft to have good flying qualities for flight missions within its OFE?

2. Evaluations

2.1. Aerodynamics and Static Stability

(a) (b) (c)

Fig. 1. (a) Baseline-II BWB CAD model; (b) LST-1 Wind Tunnel; (c) Baseline-II wind tunnel model.

Wind tunnel (WT) experiments is carried out in UiTM LST-1 low speed wind tunnel at Universiti Teknologi MARA with DARCS3D data acquisition (Fig. 1). The experimental setup used 3-component external balance with 1:11 scale half model with 0.35 m span, 0.04 m^2 wing-body plan form area, 0.114 m mean chord and moment reference centre (or centre of gravity) at 19.8% behind the leading edge of the mean chord. Blockage ratio is calculated at 1.9 percent at zero angle of attack and increases to five percent for maximum angle of attack. All experiments were conducted at average of 35 m/s airspeed (Mach 0.11) with average air density of 1.17 kg/m^3 and average temperature of 24 degrees Celsius. The experiment aims to measure the forces and moments acting on the aircraft model for varying angles of attack and canard setting angle. The centre body in mounted on the flat, round, horizontal turn table as shown in Fig. 2. The load cell has been calibrated with maximum error of 0.5 percent at full-scale reading. The load cells are able to measure up to 50 kgf of force for each x and z axis with 25 kgf-m of y-moment. Airspeed is generated by a fan located behind the test section. The type of fan is suction axial flow fan with variable speed.

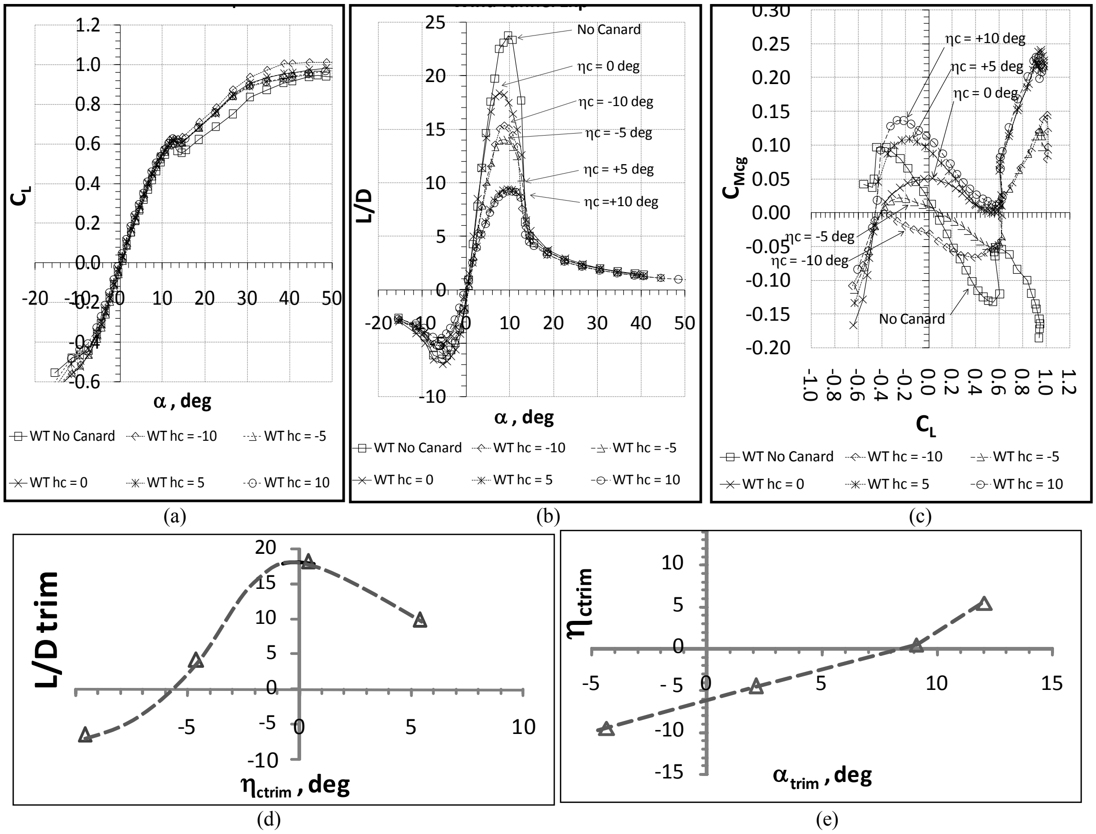


Fig. 2. (a) C_L versus α, (b) L/D versus α, (c) C_{Mcg} versus C_L, (d) $(C_L/C_D)_{trim}$ versus η_{ctrim} and (e) η_{ctrim} versus α_{ctrim} .

Fig. 2. (a) shows Baseline-II E2's C_L versus α plots for various η_c. The trend of these plots is linear at $-5° \leq \alpha \leq +10°$ that corresponds to $-0.4 \leq C_L \leq +0.6$ where the change of lift with respect to angle of attack $C_{L\alpha}$ is almost constant at around 0.05 to 0.06 per degree. There are reductions of C_L within $+10° \leq \alpha \leq +15°$. Beyond these, C_L continues to rise up to their maximum (stall) of C_{Lmax} = 0.9-1.0 at $\alpha_{stall} \cong +45$. The existence of C_L reduction within $+10° \leq \alpha \leq +15°$ is unusual but not unique to Baseline-II BWB. Similar trend is also observed on other BWB aircrafts such as studied by Katz et. al. [5]. $C_{L\alpha}$ drops to 0.03 per degree at high α. Fig. 2 (b) shows L/D versus α plots. No-canard case maximum *L/D* is equals to 23.8. Installation of canard increases drag and reduces aerodynamic efficiency. Large η_c brings maximum *L/D* even further down. Logical comprehension of this is that larger absolute η_c causes larger drag, increases downwash and reduces effective lift generated by the wing-body region thus decreases *L/D*. The best canard angle configuration seem to be near zero η_c which gives maximum *L/D* = 18.2. Fig.2 (c) shows C_{Mcg} versus C_L plots. The centre of gravity is at $h = 0.198c$. Within $-5° \leq \alpha \leq +10°$, this aircraft is longitudinally stable as it has negative changes of C_{Mcg} w.r.t. α ($dC_{Mcg}/d\alpha = C_{M\alpha}$) and C_L ($dC_{Mcg}/dC_L = -K_n$). Canard affects two parameters crucial in determining static stability of an aircraft;

- Effect of η_c to $C_{M\alpha}$ and K_n - Negative K_n means that the centre of gravity is in front of aircraft's aerodynamic centre. K_n is approximately 31.3%*c* for canard-less case while with-canard cases, K_n drops to around 6.0% to 20.4%*c*. This confirms that a canard shifts aircraft's aerodynamic centre forward.
- Effect of η_c to C_{Mcg} at zero C_L (C_{Mo}) - C_{Mo} shall be positive value for stable flight, hence positive α_{trim} (α at zero C_{Mcg}). Large C_{Mo} causes large α_{trim} (Fig 2 (c) adn (d)) and this is a standard feature of many conventional aircrafts. Maximum *L/D* at trim flight (L/D_{trim}) can be found at η_c slightly below 0.0°. This corresponds to $C_L \cong 0.45$, $\alpha_{trim} \cong 7.5°$and $L/D_{trim} = 18.2$. This will be the optimum flight condition for cruising. The change of

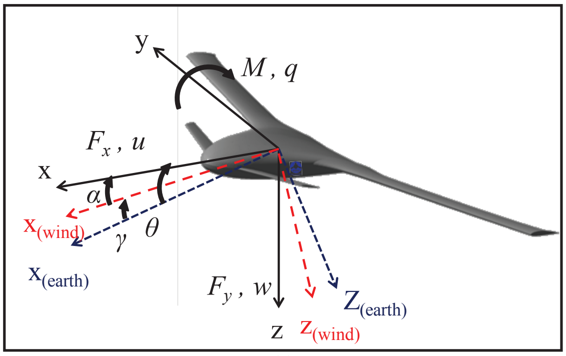
C_{Mo} with respect to the change of η_c is around 0.006 to 0.01 per degree and this is fairly small. Beyond $-5° \leq \alpha \leq +10°$, stability reversals (unstable where $K_n < 0$) are found on both positive and negative ends.

Baseline-II BWB satisfies the requirement of static stability but only for flight within $-5° \leq \alpha \leq +10°$. Although canard "spoils" the high *L/D* to just mere 18.2, it is efficient enough for a small aircraft. Authors have identified a major flaw in the design of Baseline-II BWB – the location of the wing. The wing is located too far behind that nose-down moment is so strong the outer wing has to be twisted to provide counter moment, and the canard size has to be large and located far forward of the wing. This also causes large downwash on the wing root, reducing its lift.

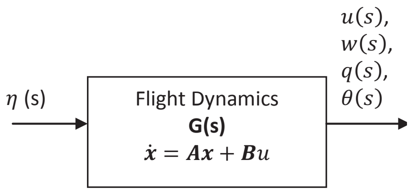
2.2. Flying Qualities

Mathematical model is derived based on results from aerodynamic and static stability plots. Longitudinal dynamics model is derived based on convention shown in Fig. 3 (a). The dynamic state-space representation is shown in Fig. 3 (b). Simulated flight is programmed within MatLab environment and a flight simulator is constructed within X-Plane software. Five airspeeds and three altitudes are chosen to be included in the study, making a total of fifteen (15) flight "points of study" within operational flight envelope limit (OFE). These missions are;

- Minimum cruise airspeed set at about 1.3 times stall speed, level flight.
- Loitering airspeed set at maximum lift-to-drag ratio, level flight.
- Optimum cruise airspeed, set at airspeed for maximum range, level flight.
- Steady climb airspeed set at maximum excess power.
- Maximum cruise airspeed set at maximum airspeed achievable by the amount of available thrust.



(a)



$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & X_q & -g\cos\theta \\ Z_u & Z_w & Z_q + U_0 & -g\sin\theta \\ M_u + M_{\dot{w}} Z_u & M_w + M_{\dot{w}} Z_w & M_q + M_{\dot{w}} U_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} X_c \\ Z_c \\ M_c \\ 0 \end{bmatrix} \eta_c$$

(b)

Fig. 3. (a) Longitudinal forces, angles and axes convention (b) flight dynamics representation.

Fig. 4. Shows results of dynamic simulations, in this case, plots of damping ratios for (a) short-period mode and (b) phugoid mode that is crucial for evaluation flying quality. To achive Level 1 quality standard, $\zeta_{sp} \geq 0.35$ while $\zeta_p \geq 0.04$. Additional requirement comes from short-period natural frequency that must adhere to specific parameter value that is less crucial for unmanned aircraft. In general, the longitudinal flying quality of Baseline-II BWB is poor. For short-period mode (Fig. 4(a)), Baseline-II BWB is unable to achieve Level 1. At near stall speed, ζ_{sp} decreases with increasing airspeed U_o but stays constant at 60 m/s onward until reaching its maximum U_o. Moving the centre of gravity forward, hence increases K_n, has only made the ζ_{sp} to decrease further from 0.1 at $K_n = 0.1$ to 0.075 at $K_n = 0.2$. Shifting the centre of gravity backward towards neutral point reduces K_n and improves ζ_{sp} but even at $K_n = 0.01$ the ζ_{sp} is still unable to achieve minimal damping ratio of 0.35 required by MIL-F-8785C. ζ_{sp} is less affected by altitude h.

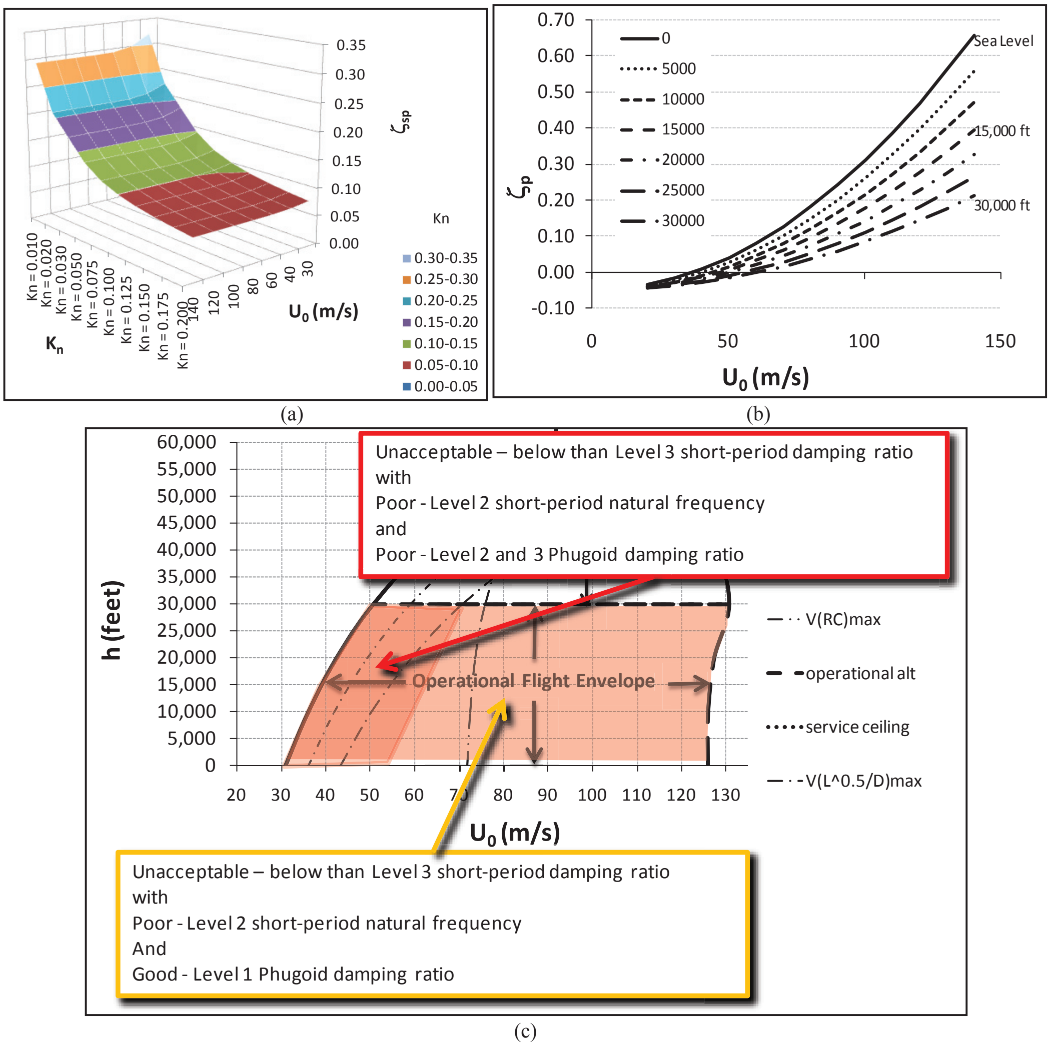


Fig. 4. (a) ζ_{sp} versus U_o versus K_n, (b) ζ_p versus U_o and (c) OFE hodograph showing SP and P modes flying quality level.

In the meantime, phugoid mode is affected by both airspeed and altitude. ζ_p increases parabolically with increasing U_o and increases linearly with increasing altitude. This aircraft has broad region of flight envelope that has Level 1 phugoid mode. Low speed flight, generally at $U_o < 50$ m/s, has Level 2 and 3 phugoid mode. Level 3 technically means unstable oscillation but this is allowed as long as the time to double amplitude is more than 55 seconds. Baseline-II BWB has this unstable phugoid mode for flight U_o < 40 m/s at sea level to U_o < 70 m/s at 30,000 feet altitudes. ζ_p is not affected by centre of gravity location. It was concluded that the behaviour of Baseline-II BWB can be summarized in to Table 1. It is found that since dynamic pressure Q_o is a function of U_o and air density, which is also a function of altitude, it can be used as the basis to designing stability augmentation system.

Table 1. Flying quality parameters relationships with U_o, h and Q_o.

Flying quality parameter	Relationship w.r.t. airspeed, U_0	Relationship w.r.t. altitude, h	Relationship w.r.t. dynamic pressure, Q_0
ω_{sp}	$\omega_{sp} \propto U_0$	$\omega_{sp} \propto 1/h$	$\omega_{sp} \propto \sqrt{Q_0}$
ζ_{sp}	$\zeta_{sp} \cong$ constant for all U_0	$\zeta_{sp} \propto 1/h$	$\zeta_{sp} \cong$ constant for all Q_0
ω_p	$\omega_p \propto 1/U_0$	$\omega_p \cong$ constant for all h	$\omega_p \propto Q_0^{-0.5}$
ζ_p	$\zeta_p \propto U_0^2$	$\zeta_p \propto 1/h$	$\zeta_p \propto Q_0$

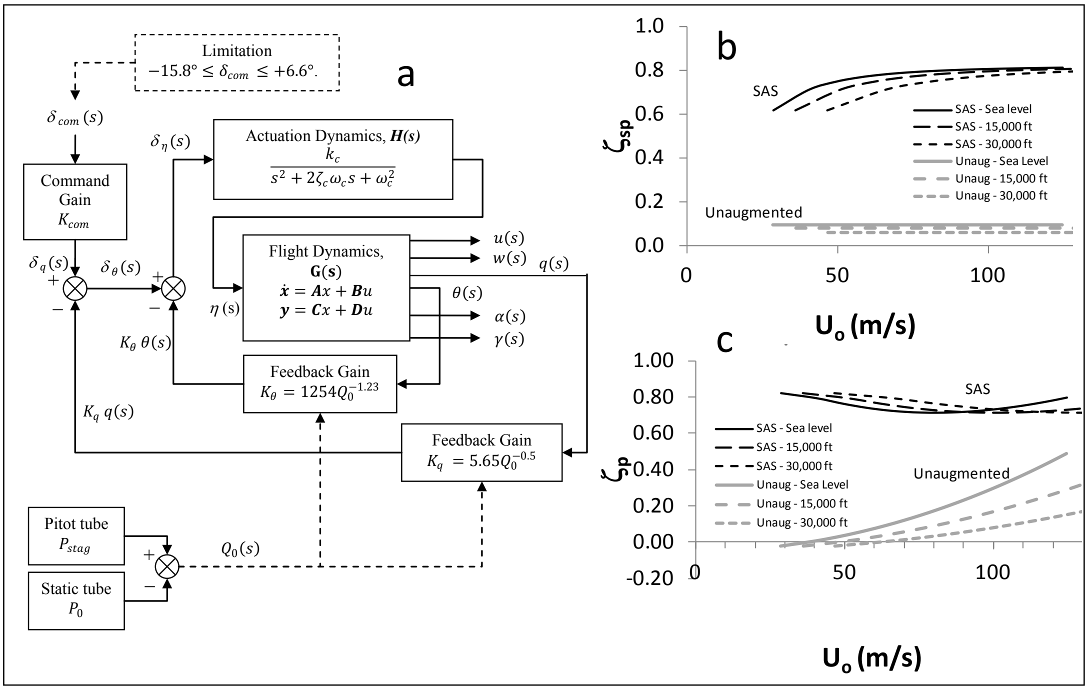


Fig. 5. (a) Proposed stability augmentation control scheme, (b) ζ_{sp} versus U_o versus K_n, (c) ζ_p versus U_o .

Stability augmentation control scheme is proposed not just to achieve Level 1 for both modes but also to have excellent damping ratios for future, more-accurate flight-path control programme. Fig. 5 shows this scheme and the flight dynamic model is surrounded by second order actuator-canard dynamics, two loops of feedback and their governing laws, namely pitch attitude feedback with variable gain K_θ and pitch rate feedback with variable gain K_q, that are also fed by dynamic pressure Q_o data from pitot-static tubes. The command is of pitch rate command, δ_{com}, with mechanical limitations is set on the canard η_c to avoid Baseline-II BWB from going into stability reversal region. The target for this augmentation system is to achieve damping ratios of 0.7 for both short-period and phugoid modes. The feedback gains control laws are determined using root locus computation for every flight missions within OFE coupled with analytical calculations. The required gains K_θ and K_q are plotted against Q_o to come up with trends and suitable equations that govern them. These equations are simplified for ease of implementation in the proposed stability augmentation scheme. The results shows that the augmented Baseline-II BWB has $0.6 \leq \zeta_{sp} \leq 0.8$ and $0.7 \leq \zeta_p \leq 0.8$. The slight wider range of ζ_{sp} and ζ_p is due to simplication of K_θ and K_q. This combination of simple pitch rate and pitch attitude feedback governed by classical control law based on dynamic pressure proves to be adequate to provide excellent damping ratios for accurate navigation and more than adequate to achieve Level 1 longitudinal flying qualities.

3. Concluding Remarks

The need to adequately trim the flight and ensuring stability (static) at usable range of angle of attack reduces aerodynamic efficiency of Baseline-II BWB to just mere L/D = 18.2. The chosen centre of gravity location gives good static stability but not enough to achieve Level 1 short-period mode damping ratio. The phugoid mode, however, achieve Level 1 in most area within its OFE but this may be due to low specification stated in MIL-F-8785C standard. The proposed stability augmentation scheme based on classical approach that consists of pitch rate and pitch attitude feedbacks with gains governed by dynamic pressure gives good longitudinal flying quality exceeding minimal values stated in the standard.

Despite gaining good flying quality the biggest setback is the loss of L/D value due to installation of canard due to wing location that is at the rear of the body. Several improvements are proposed to improve this, 1. Move the wing forward, reducing its nose-down stability, so smaller canard shall be installed and 2. Move the wing forward even more and have long but thin rear body section as elevator just like some birds having tails 'blended' to the body shape. Based on lessons learned from this study, authors chose the second option in which Baseline-III BWB design has been proposed and currently being studied.

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